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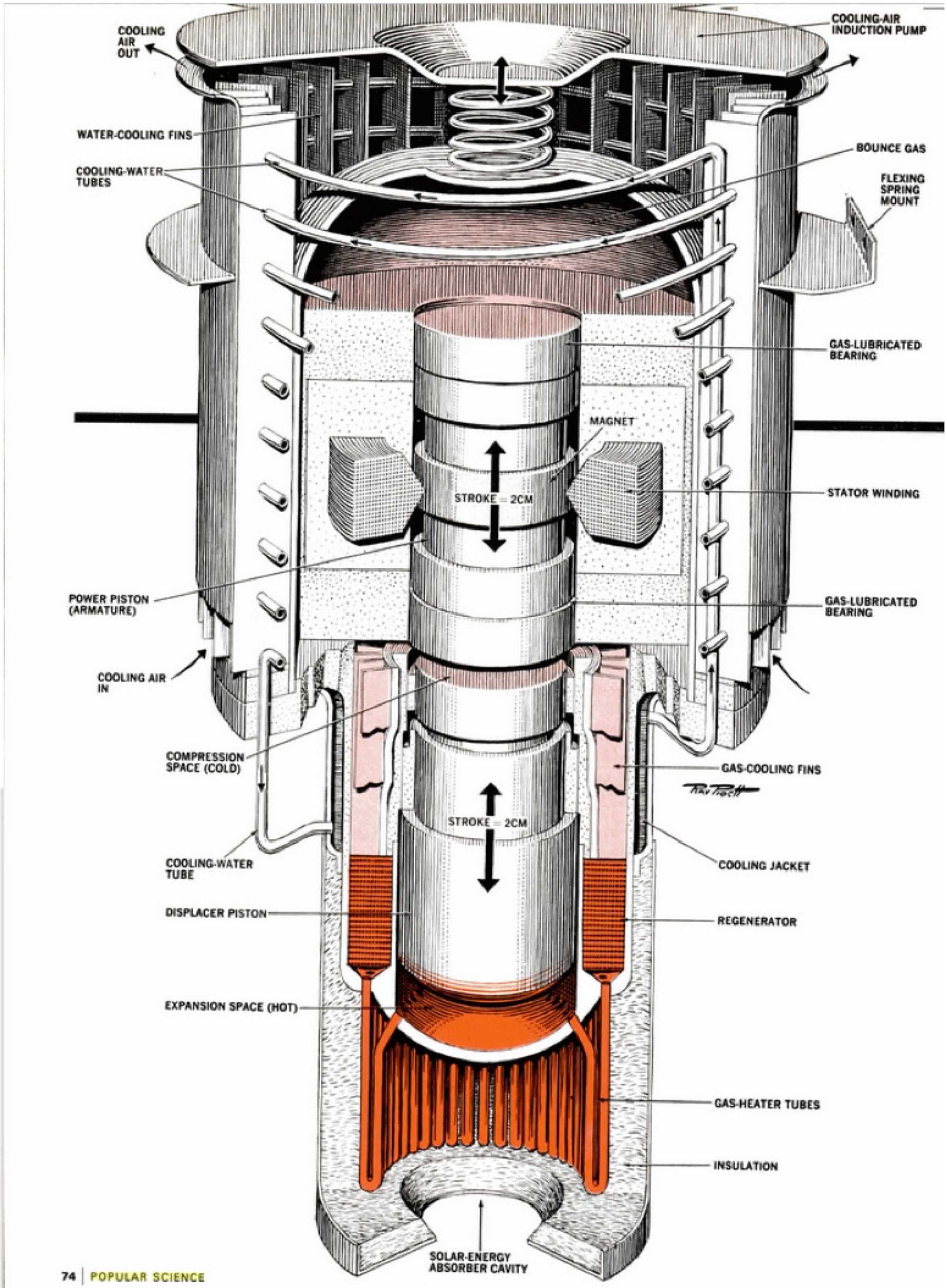
COOLING AIR OUT
COOLING-AIR INDUCTION PUMP
WATER-COOLING FINS
BOUNCE GAS
COOLING-WATER TUBES
FLEXING SPRING MOUNT
GAS-LUBRICATED BEARING
MAGNET
STROKE = 2CM
STATOR WINDING
POWER PISTON (ARMATURE)
GAS-LUBRICATED BEARING
COOLING AIR IN
COMPRESSION SPACE (COLD)
GAS-COOLING FINS
STROKE = 2CM
COOLING-WATER TUBE
COOLING JACKET
DISPLACER PISTON
REGENERATOR
EXPANSION SPACE (HOT)
GAS-HEATER TUBES
INSULATION
SOLAR-ENERGY ABSORBER CAVITY

60-cycle AC from sunshine:

Solar Stirling engine

Sunlight in—electricity out: A 162-year-old process, updated, makes it happen

By E. F. LINDSLEY

Concentrated sunlight in; 60-Hz electric power out. That's the promise of a new, highly efficient Stirling engine and one-kW electrical generator now to be tested at California's Table Mountain. For the past few months, a smaller, 10-W prototype has been running in the sunshine near NASA's Jet Propulsion Laboratory in Pasadena.

The unit is only one of many solar-electric conversion schemes JPL is testing—part of the Department of Energy's investigation of alternate energy sources. But this solar application of the Stirling engine may be the most practical way yet of producing usable AC power directly from the sun. The developer, William Beale of Sunpower Inc. in Athens, Ohio, says his Stirling engine/generator con-

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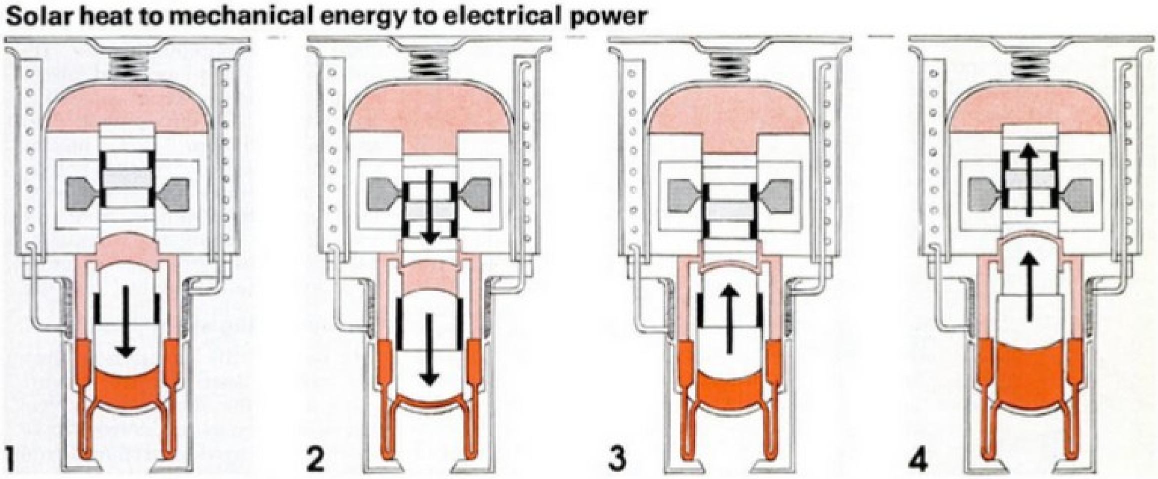
Solar heat to mechanical energy to electrical power



Sunshine-powered engine (left) is a sealed cylinder filled with pressurized helium. Helium is working gas, expand-
helium. Helium is working gas, expand-
ing and contracting to drive pistons, and is shunted between hot and cold space by displacer. It also is a bounce gas, reacting spring-like to cushion piston reversals and push pistons back. When displaced by the displacer piston, the gas moves from hot expansion space through heater tubes, where it's warmed by concentrated solar energy. Moving further, the gas passes through regenerator and stores some of its heat in closely spaced layers of foil. Next the gas flows to the finned cooling area, which chills it still further before it enters cold compression space. The fins in the cooling jacket are themselves cooled by circulating water which vaporizes, then is condensed in the coiled cooling-
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water tubes. A diaphragm-type air-induction pump pulses with the engine, and induces airflow past the water tubes and alternator. Alternator is simply a stator coil and a permanent magnet around the power piston. As the piston shuttles back and forth it repeatedly alternates the flux flow through the stator coil to generate power.

Key to the system: the varying volume of the working space above and below the displacer. When gas pressure in the compression space shoves the displacer down (1 above), gas in hot-end expansion space is forced through regenerator into cold compression space. As displacer continues moving (2) bounce-gas pressure overcomes
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cool working-gas pressure and kicks power piston down, reducing working space and compressing gas. But the bottom of displacer is larger—and now hotter—than its top. This causes a pressure differential between the gases at each end, forcing the displacer back up (3). It shoves cold gas out and down through the regenerator and heater tubes, returning heat to the gas. Then the gas flows into the hot-end space (4) and pushes up both pistons. The gas pressure in the hot-end space then drops and gas in the compression space bounces the displacer back (1), completing the cycle.

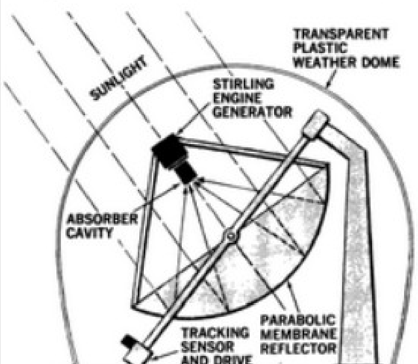
verts at least 23 percent of the solar energy it receives into electric power.

The Stirling engine dates back to 1816, when the Rev. Robert Stirling, a Scottish clergyman, developed an engine that could be powered by any heat source. In a Stirling engine, heat is applied to the outside of a sealed engine chamber. Inside, a pressurized gas shuttles back and forth between the heated space and a cooling chamber. During this cycle, the gas expands and contracts to drive a set of pistons.

Versatile free-piston design

In recent years, concern about exhaust emissions in conventional internal-combustion engines has renewed interest in the Stirling engine [PS, Feb. '73]. But unlike Stirling engines designed for autos, Beale's version is a free-piston design. The two pistons have no mechanical linkages—they simply slide back and forth, generating a reciprocal motion that can do a number of jobs.

When I first reported on it [PS, Aug. '74], the Beale Stirling engine was powering an air conditioner. (General Electric's Space Division is now working on this concept. They're developing a heat pump powered by a gas-fired Stirling engine.) Like that earlier model, Beale's Stirling engine/generator has only two moving parts—a displacer piston and a power piston. Both operate in an atmosphere of highly pressurized helium gas inside a sealed housing. The power piston doubles as an armature: As



Projected system shown might have better than 23-percent efficiency, says Beale, even if dome transmits only 85 percent of sunlight to parabolic mirror. That reflects 85 percent to engine, which converts 45 percent of absorbed heat to mechanical energy. Engine's alternator converts 85 percent of that to electricity.

it shuttles back and forth, it acts as the moving element in the electrical generation process.

The illustrations show how this free-piston Stirling works. (Although there's no "up" or "down" in the engine, we've used these terms for ease of understanding.) If you have trouble understanding it, you are not alone. Both Beale and Anthony Giandemonico, project engineer at JPL, concede that it's difficult to explain.

My own view may offend purists, but I visualize a Stirling as a steam engine with a built-in boiler. The working gas is heated at the hot end like steam in a boiler—and it expands like steam to do work. The displacer then moves the spent gas to the cold end where it is reduced in volume and pressure, much like steam in a condenser.

Sunlight-electricity conversion

In Beale's solar-powered version of a Stirling engine, a reflector focuses the sun's rays on the engine. The sun's enormous energy is then concentrated into an intensely hot spot and trapped in the absorber cavity of the sealed cylinder. Then it heats the high-pressure helium gas within.

Inside, the power piston shuttles in an unfailing 60-Hz rhythm. Electrical leads bring the power out ready for transmission to the user. There are no intermediate processes using steam, chemicals, or complex electronic gear. Nor are there any drifting clouds of smoke or hard-to-dispose residual wastes.

Simplicity is one advantage of a Stirling engine. Another is fuel flexibility: Heat from the sun, a gas flame, or even burning buffalo chips will drive it. Beale talks of running his solar engine in developing countries, using a simple wood fire when sunlight is inadequate. Such power plants could suffice for modest, local needs. He also pictures larger, more sophisticated solar Stirling generators massed and paralleled to deliver power in quantity—as pictured on our cover.

Ideally, these Stirling power plants would be built where the desert sky is a burning, blue bowl overhead. Marching across the desert would be ranks of gleaming, mirror-faced, parabolic reflectors. Slowly, almost imperceptibly, they'd turn to track the sun. A Stirling engine/generator mounted at the focal point of each reflector would convert some 23 percent of that captured solar energy into electricity—maybe more.

Beale stresses that his figures are very conservative. Giandemonico agrees that Beale's anticipated 23 percent is probably valid. That estimate appears to be better than the present capabilities of photovoltaic or other forms of solar conversion (perhaps 15 percent). Why this unusual efficiency?

- There are only two moving parts, with no rotating components or bearings.
- Gas is the only lubricant.
- Inertial forces are absorbed by the bounce gas.
- There is no governor or throttle.

Energy conversion takes place like a well-executed double play—solar heat to mechanical energy to electrical power, all within the sealed capsule. You aren't converting linear piston motion into rotating shaft movement, as most engines do. This eliminates connecting rods, bearings, shaft seals, and the windage effect of whirling parts. With no bearings, there is no need for lubrication. Gas lubricates the working piston.

Without valves that themselves require power to open and close, there are no pumping losses. It's true that the displacer and piston must stop and reverse at the end of each stroke, but because of their reciprocal motion, the inertial force is absorbed by the helium gas that bounces the part back. This is quite different from the wasteful way in which a connecting rod and crank stop piston movement by brute mechanical limiting.

Steady cycling at any load

In spite of the fact that it shuttles rather than rotates, Beale's linear alternator produces a typical sine wave. Just as in a conventional generator, current is produced in a coil of wire by intercepting a changing magnetic field. Beale uses a permanent magnet flux source, though a field coil and field current may ultimately be necessary for regulating current and voltage. He's tried a number of configurations. The two basic ones are a cylindrical permanent magnet with a wire-wound armature shuttling inside, and a wound stator with a permanent magnet shuttling inside. There are some problems with both, but basically, whatever can be done with a rotating alternator can probably also be done with this linear type.

Bright California sunshine runs miniature Stirling engine/generator (above) as engineers check operation. Solar power for this 10-W unit is concentrated by a Fresnel lens at the base of pyramid-shaped collector. At right, the same unit is inverted so heat from a gas torch can be used to power it. At rear, inventor William Beale adjusts resistance load in the generator's output.

Particularly amazing, to old generator hands at least, is the fact that Beale's Stirling linear alternator holds 60-Hz output frequency at no load, full load, and anywhere in between—without a governor or a throttle. This is a built-in function of the carefully tailored masses, and the helium's bounce and spring characteristics. Even more remarkable, frequency is not affected by changes in heat input.

Power output, however, is affected. I watched as this was demonstrated in Beale's lab. Because of a snowstorm, an associate brought in a small, 10-W model that had been running outside. Beale inverted the engine and heated it with a propane torch (see photo). After a brief heat-up period, he started the engine. The dial showed 60 Hz, no load. Beale dropped resistance load into the output circuit, varied it, and cut it in and out, but the frequency stayed constant. Removing the torch heat and letting the engine coast on residual heat brought a gradual reduction in output—but again the frequency remained unchanged until power stopped completely. Compare this to a diesel or other engine-driven alternator, which, to hold frequency, needs a very precise and expensive governor making constant, minute throttle adjustments.

Accurate frequency control is especially important when you're paralleling one or more generators. To merge the outputs, the oncoming unit must be in phase and at the same frequency as the line or other unit. At large generating stations, electric sensors monitor the out-of-phase condition, and throw the switch only when the sine waves are in phase. Try to parallel with the sine waves out of step and dramatic electrical nasties happen.

Economics of scale

If Beale's solar Stirling generators are ever to be used for big outputs, paralleling is probably essential. Although the engine is relatively inexpensive and easy to build, as you scale it up the reflector and tracking mount can reach impractical and costly sizes quite quickly. Thus, paralleled multiple units of economical size appear most attractive. An alternative might be conversion to DC for battery charging. This, too, could prove practical when large utility battery storage facilities are developed.

Beale would also like to simplify the solar-collecting equipment. The reflector his rig will share with other projects at JPL has a massive structure and a necessarily husky tracking drive. "But the reflector doesn't have to be a big, heavy casting like a telescope mirror," Beale says. He talks about using inflated plastic reflectors, or parabolic membranes made of Teflon and shaped like a concave bubble. "The beauty of it is," says Beale, "that the parabolic membrane is actually more accurate in its geometrical configuration than these extremely expensive things." For now, however, until the membrane paraboloids become available, his engine will be tested on the heavier rig.

I asked Beale about ways he might improve his present one-kW test model. Wouldn't it stabilize output, for example, if the absorber head contained something to regulate heat input?

He agreed to some extent. "Heat sinks? They could do some good, for example here in Ohio, where the sun shines intermittently. But many applications in really bright desert areas wouldn't need them."

I asked Giandemonico at JPL about the size and output of the one-kW test unit. To me that seemed very small. He agreed: "That's the next step, to build bigger engines." But then he added a shocker. "We ran into ASME boiler-code restrictions. They're going to require our engine to be bigger and heavier than Beale's prototype. The whole thing qualifies as a pressure vessel."

JPL seems willing, however, to accept this. The attitude appeared to be that weight is not so important as getting a larger model on line to check for shortcomings.

Though design modifications may be needed on larger models, Beale's current engines run quietly, smoothly, and at fairly high speed. His combined engine/generator is truly elegant. Later, after JPL's tests this summer, we'll let you know how it shapes up as a future power source. And, when GE is ready to talk about the Stirling-powered heat pump, we'll update you on that, too. PS